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Simultaneous observations of the 2-day wave at London (43°N, 81°W) and Saskatoon (52°N, 107°W) near 91 km altitude during the two years of 1993 and 1994

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Abstract. Simultaneous observations are valuable in providing further insights into the character of the quasi 2-day wave. In this study we investigate the period and amplitude for the quasi 2-day wave near 91 km using MF radars at London and Saskatoon, Canada, and in addition look at possible values of the zonal wave number. The results of the present study bring out certain new aspects of the quasi 2-day wave at mid-latitudes in the Northern Hemisphere. In particular we show that the period of the quasi 2-day wave determined from our study (specially at large amplitudes) is smaller (46–47 h) than the 51–52 h period often suggested by other Northern Hemisphere results, and that the periods also showed variability as a function of time. We also draw attention to the annual variability, and especially highlight the occurrence of the wave in non-summer months. Our observations show significant wave correlation between the London and Saskatoon sites during time intervals of strong 2-day wave activity. These results suggest that the 2-day waves of 1993/4 are westward propagating waves of zonal wave number 3, although sometimes the zonal wave number 5 is also indicated (specially at large amplitudes). Our study also contributes additional mid-latitude geographical data which should aid in developing a better picture of the quasi 2-day wave.

1 Introduction

The quasi 2-day wave (hereafter referred to as the 2-day wave) is a global-scale oscillation in the middle atmosphere (in the 50–100 km height region) which has been observed in both the Northern and Southern Hemispheres by radar, rocket, and satellite techniques for over 20 years (e.g., Muller, 1972; Coy, 1979; Craig *et al.*, 1980; Rodgers and Prata, 1981; Burks and Leovy, 1986; Plumb *et al.*, 1987; Tsuda *et al.*, 1988; Reddi *et al.*, 1988; Poole, 1990; Clark *et al.*, 1994; Harris, 1993; Wu *et al.*, 1993; Fritts and Isler, 1994; Meek *et al.*, 1996). However, the generating mechanisms and its role in the middle atmosphere are still require amplification.

Most observations suggest that the 2-day wave is a late summer phenomenon in the middle atmosphere, occurs mainly at low- and mid-latitudes, and reaches its maximum amplitude in late July/early August in the Northern Hemisphere and in late January/early February in the Southern Hemisphere (e.g., Kingsley *et al.*, 1978; Craig and Elford, 1981; Manson and Meek, 1986; Clark, 1989; Plumb *et al.*, 1987; Clark *et al.*, 1994; Harris, 1993). In general, radar observations in the Northern Hemisphere indicate the presence of a 2-day wave in all seasons, although maximum amplitudes occur in the months of July/August (e.g., Kingsley *et al.*, 1978; Manson *et al.*, 1982; Manson and Meek, 1986; Clark, 1989; Tsuda *et al.*, 1988). A subsidiary weak maximum is often observed in the autumn or winter (e.g., Muller and Nelson, 1978; Craig and Elford, 1981; Ito *et al.*, 1984; Harris, 1993b), but at other times of the year the oscillation is usually either weak (amplitude indistinguishable from noise) or non-existent, depending on the locality (e.g., Rodgers and Prata, 1981).

Most radar observations show that 2-day oscillations have larger meridional component amplitudes as compared to the zonal component amplitudes at mid-latitudes. In general, the meridional component is larger than the zonal component at mid-latitudes by a factor of 2–3 times. Maximum amplitudes are usually attained at heights between 80 and 95 km (e.g., Craig *et al.*, 1980; Craig *et al.*, 1981; Clark, 1989; Clark *et al.*, 1994; Tsuda *et al.*, 1988; Ito *et al.*, 1984).

Both ground-based and satellite observations show that amplitudes in the meridional component are larger in the Southern Hemisphere, being up to a factor of two larger than those found in the Northern Hemisphere

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(e.g., Rodgers and Prata, 1981; Plumb *et al.*, 1987, Tsuda *et al.*, 1988; Clark, 1989; Clark *et al.*, 1994; Ito *et al.*, 1984). Typical mean maximum amplitudes in the meridional component are ~30–40 m/s but short-term amplitudes of 50–100 m/s are common in the Southern Hemisphere (e.g., Craig *et al.*, 1980; Craig and Elford, 1981; Phillips, 1989). In contrast, mean maximum amplitudes near 20–30 m/s are typical in the Northern Hemisphere (e.g., Rodgers and Prata, 1981; Tsuda *et al.*, 1988; Clark, 1989; Clark *et al.*, 1994). The duration of all such events ranges from several days to intervals in excess of a month.

In addition to amplitude differences, another apparent contrast between the hemispheres in their respective summers is the wave period. Different observers report somewhat different periods in the range 43–53 h (e.g., Craig and Elford, 1981; Kalchenko, 1987; Salby and Roper, 1980; Massebeuf *et al.*, 1981; Manson *et al.*, 1982; Cevolani *et al.*, 1983; Tsuda *et al.*, 1988). In the Southern summer Hemisphere the dominant wave period seems consistently to be fairly close to 48 ± 3 h (e.g., Craig *et al.*, 1980; Craig and Elford, 1981; Phillips, 1989; Poole, 1990; Harris, 1993b), whereas in the Northern summer Hemisphere the period often seems to be 51 ± 2 hours (e.g., Muller, 1972; Glass *et al.*, 1975; Muller and Nelson, 1978; Kingsley *et al.*, 1978; Stenning *et al.*, 1978; Manson *et al.*, 1978; Salby and Roper, 1980; Tsuda *et al.*, 1988). Manson *et al.* (1982) reported summer (June–August) values of 47–50 (±2–5) h. It is possible that these differences are due to hemispheric differences in the wave forcing and/or propagation conditions in the middle atmosphere. More precise information about the wave period is required if the source of the waves is to be determined.

Simultaneous meteor wind measurements at Garchy (47°N, 3°E) and Obninsk (56°N, 36°E), led Glass *et al.* (1975) to propose that the 2-day wave was a westward-propagating third order Rossby-gravity normal mode; the (3, 0) mode (Longuet-Higgins, 1968). This proposal was further substantiated by simultaneous observations of the 2-day wave by various investigators. Most observations in the Southern and Northern Hemispheres generally suggest that the 2-day wave is consistent with a westward propagating wave of zonal wave number 3 (e.g., Muller and Nelson, 1978; Craig *et al.*, 1983; Phillips, 1989; Poole, 1990; Clark *et al.*, 1993). This is also supported by satellite temperature observations (e.g., Rodgers and Prata, 1981; Wu *et al.*, 1993). On the other hand, a comparative measurement over the relatively long baseline between Sheffield (England) and Durham (USA) indicated a value for the zonal wave number of 2 (Clark, 1983). Three-station observations of the long period oscillation showed that the zonal wave number can have values from 2 to 4 for different wave periods ranging from 36 to 60 hours (Cevolani *et al.*, 1983). Randel (1993) showed evidence that the 2-day wave can have zonal wave numbers 3–4 with periods near 2 days. Recently, Meek *et al.* (1996) found a zonal wave number 4, for the Northern Hemisphere 1992 wave, by combining data from nine meteor and MF radars around the globe. For the 1991 event, zonal wave numbers 3 and 4 were possible. Within that paper, model calculation showed that waves with zonal wave numbers 3 and 4 have significant amplitudes. A zonal wave number 5 was reported by Kalchenko (1987). The theoretical understanding, numerical simulations, and resumé of advances in 2-day wave studies are contained in (amongst others) Salby (1981), Hunt (1981), Plumb (1983), Pfister (1985), and Hagan *et al.* (1993).

One interpretation put forward to explain the existence of the wave is that it is a manifestation of the Rossby-gravity (3, 0) normal mode forced by the lower atmosphere (Salby and Roper, 1980; Salby, 1981). Salby (1981) attributed the excitation source of the wave to the characteristic unsteadiness of the tropospheric flow, or tropospheric "noise". Salby (1981) studied the 2-day wave theoretically and showed that the third order Rossby-gravity mode has magnified responses very near 53 hours (2.2 days for solstice condition) in the presence of realistic numerical simulations of mean wind and temperature structures. While Salby's (1981) theory explains many of the observed features of the 2-day wave, it still has to explain the different hemispheric response in amplitude and in wave period.

An alternative interpretation proposed by Plumb (1983) emphasized the role of the fast growing baroclinic instability above the summer stratospheric westward jet. In this theory, the 2-day wave is believed to be a product of the instabilty. A zonal wave number 3 is predicted. His results were based on a one-dimensional stability analysis. Pfister (1985) extended the stability analyses to two-dimensions, and again found peaks in the unstable wave growth at zonal wave numbers 2–4, with periods of 1.4–3 days. Recently, Hagan *et al.* (1993) performed a series of numerical experiments for summer conditions (particularly for the January month) in the Southern Hemisphere using a linearized spectral model which includes realistic mean winds and dissipation. The results provide further evidence that the 2-day wave observed in the upper mesosphere may be a signature of the westward propagating, zonal wave number 3 mixed Rossby-gravity mode (Salby, 1981).

Therefore, there is no conclusive evidence pointing to the source of the 2-day wave observed at mesospheric heights, but the aforementioned theoretical understandings and major conclusions continue to be qualitatively consistent with recent observational results. Further observations are required in order to resolve questions about the generating mechanism as well as to understand better the role of the wave in the middle atmosphere. Better understanding of the waves is important because of the interaction between the waves and the mean flow. There is important implications for the general circulation of the middle atmosphere during the summer. The waves may also be important in the transport of atmospheric constituents at mesospheric heights during the summer (Plumb *et al.*, 1987). In this study we investigate the period and amplitude of the waves over two years, and look for possible values of the zonal wave number for the quasi 2-day wave, using MF radars located at London and Saskatoon, Canada.

2 Data analysis methods

Winds in the mesosphere and lower thermosphere over London (43°N, 81°W) and Saskatoon (52°N, 107°W) have been regularly monitored using MF radars since November 1992 and September 1978, respectively. The radar frequency of both radars is 2.2 MHz, and they have been used to measure horizontal winds in the 80–100 km height range using the spaced antenna method. Winds measurements are made at time intervals of 5 min and at 3 km height intervals. A more detailed description of the MF radar systems can be found elsewhere (e.g., Thayaparan, 1995; Thayaparan *et al.*, 1995a; Gregory *et al.*, 1979; Meek, 1980).

The present study of the 2-day wave is based on data collected during the years 1993 and 1994. This study focuses mainly on comparisons performed at 91 km height which is generally the maximum amplitude peak of the 2-day wave activity at both sites. Since we are here only interested in long-period phenomena the data were averaged over 1 h in the analysis. Missing hourly averages (which were rare) were replaced by Gaussian distributed random noises with a variance matching that of the data itself (e.g., Park and Muller, 1988; Ball, 1981).

The observed 2-day wave usually has its maximum somewhat after the summer solstice, perhaps indicating a particularly effective forcing agent present at this time. If this is correct then a more precise measurement of the wave period is required, so that it may give a better clue to the source of the wave. To determine the precise period of the 2-day oscillation, we used a complex demodulation method which is very sensitive to the frequency variations within the time series (e.g., Harris, 1993; Harris and Vincent, 1993; Palo and Avery, 1993; Thayaparan *et al.*, 1997). It should be emphasized that we have used this complex demodulation method to investigate the period of the 2-day wave but have used standard harmonic analysis method to estimate the amplitudes of the 2-day wave. The advantages and disadvantages of these methods will be discussed in the following subsections.

2.1 Complex demodulation

The complex demodulation method effectively investigates one frequency range at a time (e.g., Bloomfield, 1976; Brillinger and Krishnaiah, 1983). The basic idea can be explained as follows. If ω_0 ($\omega_0 = 2\pi f_0$, f_0 being the frequency closest to the frequency of interest) is known a priori, we can study the time-dependent behavior of the time series by shifting ("beating") its frequency down to zero. This beating is easily accomplished by multiplying the raw time series by $\exp(-i\omega_0 t)$ or with an equivalent frequency shift in the Fourier domain. The resultant complex time series is then low-pass filtered about the zero frequency, thus coherently demodulating the original time series around the frequency of f_0 (demodulation frequency). It should be noted that the amplitude spectrum of the complex demodulated time series is just a frequency shifted version of the original time series spectrum. The phase gradient, i.e., the rate of change of the phase of the complex demodulated time series, is a measure of the "local" frequency difference from the demodulation frequency, i.e., $f - f_0 = \frac{1}{2\pi}\frac{d\Phi}{dt}$. Thus, if a time series contains a harmonic component with the frequency f we can detect the presence of this component by plotting the phase, Φ, as a function of time, t. This plot is approximately linear (see below), and we can get an precise estimate of the dominant period of the 2-day wave as function of time.

We performed several tests by varying the demodulation frequency, and it turns out that the period determined in this manner is independent of the demodulation frequency as long as the strong signal remains within the bandpass. As the demodulation frequency moves closer to the dominant frequency, the slope of the phase of the complex demodulation approaches zero. This provides a consistency check on the results of the complex demodulation method. If the period estimate remains the same as the demodulation frequency is varied then it is highly likely that a dominant signal is present within the bandpass. Otherwise the determined periods may be simply random noise. One of the advantages of the complex demodulation method is that it allows an estimate of the frequency of the dominant component as a function of time within the time series. Thus variations of the period with time can be studied, and statistics formed. This is precisely what was done for the 2-day wave analysis in Sect. 5. It should be borne in mind that there are cases where the complex demodulation method would provide erroneous results. For example, if there are multiple signals present in the bandwidth then the complex demodulation method would provide an estimate of the center of mass for the power spectra in the bandpass used. However, our analysis suggests that the 2-day wave is by far the dominant component, as will be seen later.

Following these tests, we decided to use a 48-hour demodulation period in this study. An effective band-pass filter was used with limits from 42 to 54 h for the 48-h demodulation period in this study, and the spectrum was shifted to 0 Hz. Because we deal with only one component, e.g., meridional, the amplitude is reduced by a factor of 2, since we lose the information at negative frequency. However, because the data are purely real, the spectrum is symmetric and therefore we retain all the pertinent phase information. Amplitudes only need to be rescaled to obtain their proper values and we have done this, although we have not presented these because our emphasis is on studies of phases and periods.

The periods have been estimated from the demodulated time series from day 152 to day 273 (from June 1 to September 30), which allows amplitude variations on time scales greater than 8 days. We have used several different types of spectral windows in order to confirm the consistency of our results. For example, we used firstly a Hamming window (Harris, 1978) and then also tried a flat window with equal weighting except for the end values which have only half the weighting (e.g., Harris, 1993a). This gave enough tapering to avoid spurious ringing and other effects in the filtered data (e.g., Harris, 1978; Bloomfield, 1976; Bracewell, 1978; Forbes, 1988; Harris, 1993). In all windows, we chose purely real windows so as to ensure that the filtered data have no temporal shifts relative to the raw data. All results concerning rate of change of phase and period were indistinguishable between tests. Henceforth we use the Hamming window when we use the complex demodulation procedure.

2.2 Harmonic analysis

A complex demodulation method can be used to give an estimate of the amplitude of the 2-day wave as a function of time. It has the advantage of producing a time series with a data point for every data point in the original time series. The amplitude of the complex demodulation of the time series is a measure of the amplitude of the dominant frequency within the band-pass around the demodulation frequency. However, these demodulated amplitudes can be slightly smaller than the real amplitudes because the demodulated amplitudes have been bandpass filtered. Therefore demodulated amplitudes will not be used as an estimate of the amplitude of the 2-day wave. We used standard harmonic analysis method for the estimation of the amplitudes of the 2-day wave.

There is considerable theoretical and experimental evidence that various tidal components (24-h, 12-h, and 8-h) also co-exist with the 2-day wave (e.g., Thayaparan *et al.*, 1995a, b; Manson *et al.*, 1989). Because of the presence of these strong tidal components we used four day groupings of data, stepped by one day (e.g., 1–4, 2–5, 3–6,...). A 4-day fit was adopted because this is long enough to give reasonable significance to our results yet short enough to give reasonable sensitivity during periods of large 2-day activity. The zonal (u) and meridional (v) wind components were represented as a function of time (t) by

$$u(t), v(t) = a_0 + \sum_{i=1}^{i=4} a_i \sin\left(\frac{2\pi}{T_i} t + \Phi_i\right)$$

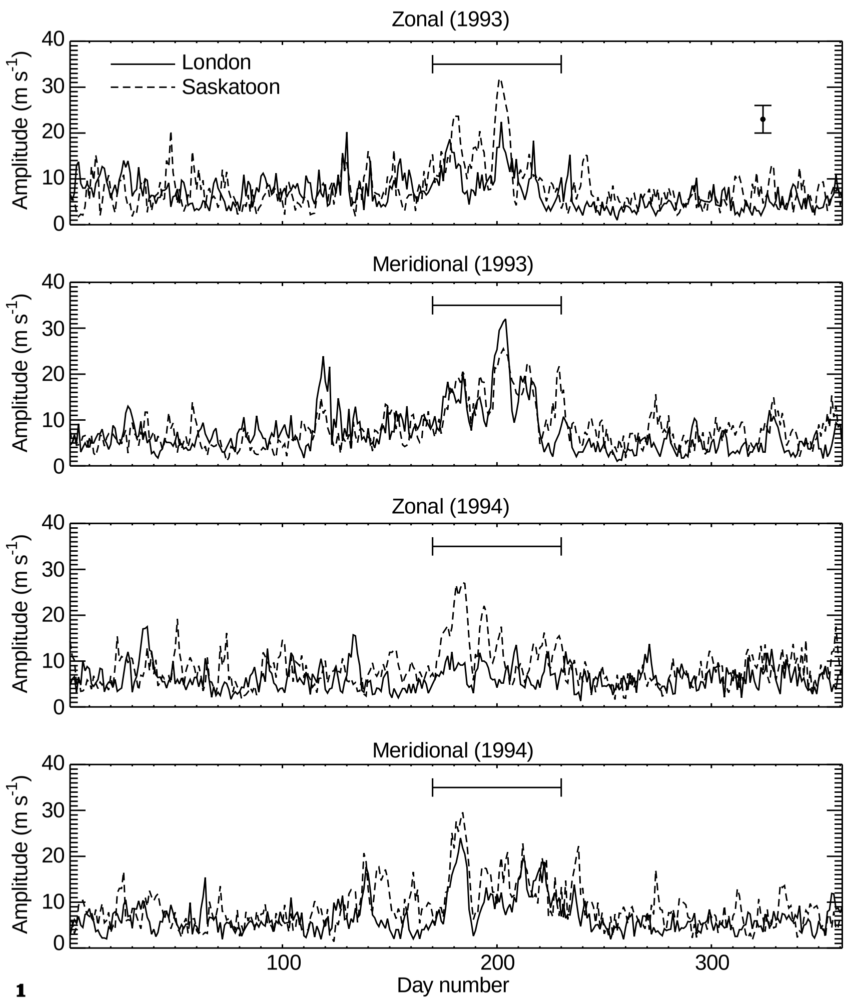
where a_0 is the prevailing mean wind and a_i and Φ_i are the mean amplitude and phase for the 8-h ($i = 1$), 12-h ($i = 2$), and 24-h ($i = 3$) tidal components. The wave period T_4 was varied systematically from 40 to 60 h in steps of 0.5-hour in order to provide maximum sensitivity to amplitude variations. For each data interval the daily 2-day wave amplitude chosen was the one with the period which produced maximum response, and these are illustrated in Fig. 1 and the corresponding periods representing the best fits to the data are illustrated in Fig. 2. This analysis was carried out for both zonal and meridional components.

3 Amplitude

Figure 1 shows the amplitudes of the 2-day wave for both the zonal and meridional components in 1993 and 1994: values of the 4-day fit are shown for each day, where the 4-day window has been slide along in one day steps. Note that the units used to display the time series is the day number. Figure 1 clearly illustrates that the 2-day wave activity has maximum amplitude during the summer months, i.e. from day number 170 (19 June) to day number 220 (8 August). However, these observations also indicate the presence of the 2-day wave more weakly at other times of the year. One noticeable feature is a pronounced maximum during the day numbers 115–125 (late April) in 1993, particularly in the meridional components of the London data. Similar behavior is also evident in both the London and Saskatoon data during the day numbers 125–150 (near mid May) in 1994. Figure 2 shows that generally the estimated periods are less variable during the summer months (i.e. from day number 170 to day number 220) than other times of the year. It should be emphasized here that outside of the summer months the estimated periods are generally less reliable owing to the comparatively small wave amplitude. Our earlier work suggests that the periods of the 2-day wave in Fig. 2 are not reliable when the amplitudes of the oscillations are less than 3 m/s (Thayaparan, 1995; Hocking and Thayaparan, 1997). The horizontal bars in Fig. 1 and 2 indicate the time periods of enhanced wave activity and this is the region discussed further in this study. The vertical error bars shown on the amplitude and period plots (in the upper panels of Fig. 1 and 2) are the 95% confidence intervals associated with each fitted parameter (Thayaparan, 1995; Hocking and Thayaparan, 1997). The rest of the discussion will be confined between day number 170 and day number 220.

Maximum amplitude values of $\sim$25–30 m/s are observed in the meridional component. For the zonal component the maximum values attain $\sim$15–20 m/s over London but very large amplitudes of 30 m/s are also observed over Saskatoon particularly in 1993. These maximum amplitude values are generally consistent with previous observations in the Northern Hemisphere (e.g., Rodgers and Prata, 1981; Tsuda *et al.*, 1988; Clark, 1989; Clark *et al.*, 1994). We also note that the amplitude of the 2-day oscillation in the zonal component is larger by a factor of 2–3 in Saskatoon than in London during the mid-summer amplitude oscillations, while the meridional component shows comparable amplitudes at both sites.

The dominance of the 2-day periodicity is also clearly evident in the filtered time series shown in Fig. 3. Note that the corresponding time segment shown in this figure is from day number 152 (1 June) to day number 270 (27 September). The data at the two sites were subjected to a band-pass filter with cutoff periods of 42 and 54 h. Figure 3 shows quite distinctly that the time variations of the occurrence of the 2-day wave are very similar at London and Saskatoon. It is apparent that the wave is transient in nature with the largest event taking the form



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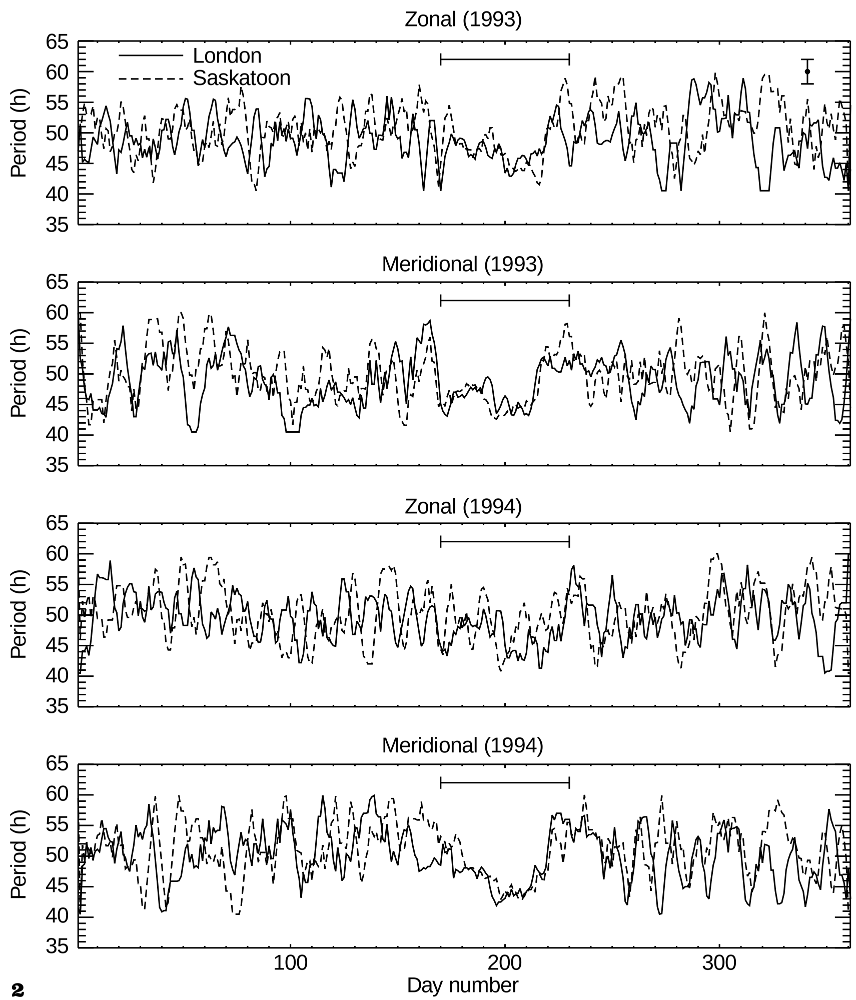

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Fig. 1. Daily amplitudes of the 2-day wave at 91 km in London and Saskatoon for the zonal and meridional components in 1993 and 1994. *Horizontal bars* indicate the time periods of enhanced wave activity and this is the region often discussed in this study. *Vertical bar* in the upper panel indicates the 95% confidence limits

Fig. 2. Daily periods of the 2-day wave at 91 km in London and Saskatoon for the zonal and meridional components in 1993 and 1994. *Horizontal bars* indicate the time periods of enhanced wave activity and this is the region often discussed in this paper. *Vertical bar* in the upper panel indicates the 95% confidence limits

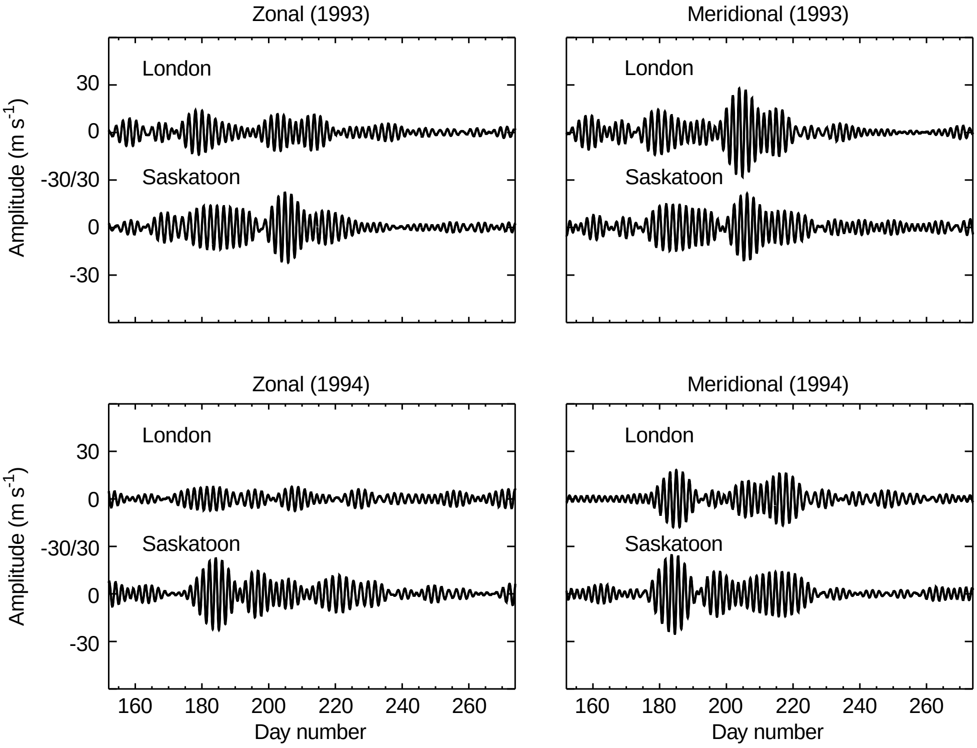

Fig. 3. (*Left*) zonal and (*right*) meridional components of the winds observed at 91 km in London and Saskatoon from day number 152 to day number 270 in 1993 and 1994. Data have been bandpass filtered to retain only periods between 42 h and 54 h

of a pulse or burst starting around day number 175 (25 June) and lasting till day number 220 (8 August). Two pronounced 2-day activity intervals occur, particularly in the meridional component during this period of time at both sites for the years 1993 and 1994. The initial burst started around day 175–180 at both sites for the years 1993 and 1994. A second burst started around day 200 in 1993, and started around day 194–196 in 1994 at both sites.

To obtain a picture of the average behavior of the amplitude and phase of the 2-day wave as a function of height, the data from the second event during 1993 are shown in Fig. 4 for both the zonal and meridional components. We use these data because the wave has the largest meridional amplitudes in this interval, i.e., from day number 201 to day number 210. The horizontal error bars shown on the amplitude and period plots are the 95% confidence intervals associated with each fitted parameter (Hocking and Thayaparan, 1997). The figure shows that the wave amplitude maximizes near 91 km at both sites and then decreases with further increase in height. A more detailed description of the vertical structure of the 2-day wave over London is given by Thayaparan *et al.* (1997).

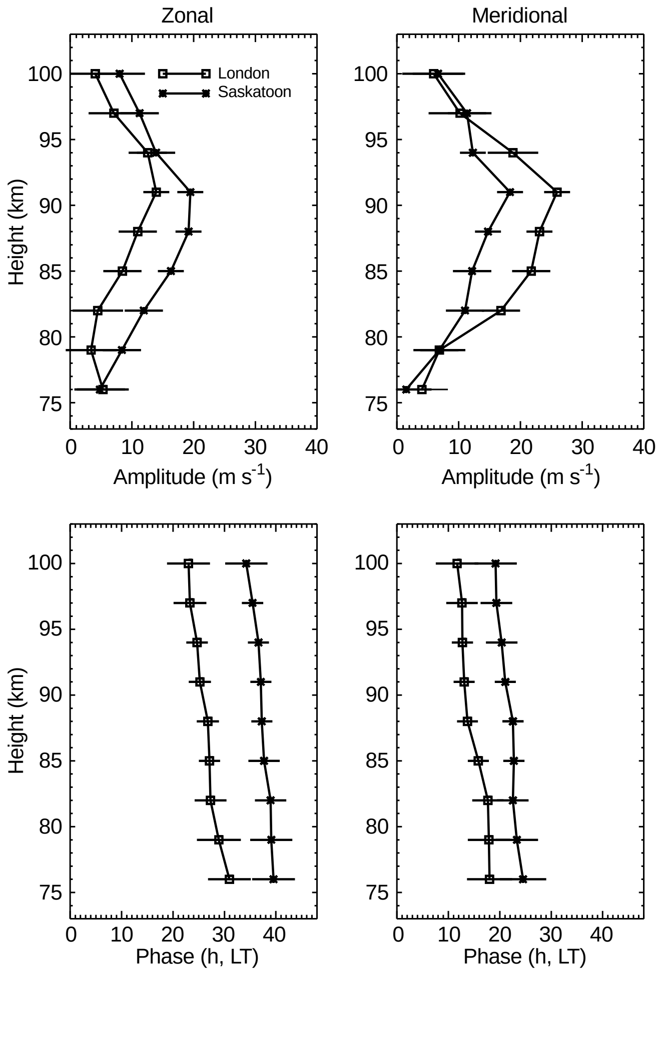

Fig. 4. Mean height profiles of the amplitude and phase during day numbers 201–210 in 1993 for the zonal and meridional components at London and Saskatoon. The phase of the 2-day wave was obtained by determining the local time of the maximum eastward and northward winds. The phase is estimated relative to 0000 LT on January 1, 1993. *Horizontal bars* indicate the 95% confidence limits

4 Phase

The phase is illustrated in Fig. 4 below each amplitude plot, again as a function of height. The phase of the 2-day wave was obtained by determining the local time of the maximum eastward and northward winds, on a scale of 0 to 48 h (see below), in which zero hours was taken to be midnight on each odd day number of the year (Thayaparan *et al.*, 1997).

The phase plots show that the meridional component leads the zonal component by 11–14 h in the 85–94 height range, indicating clockwise rotation of the wind vector (looking from above). The plots also show that the London site leads the Saskatoon site by 9–11 h for both the zonal and meridional components. The physical significance of these results will be discussed in Sect. 8.

The vertical wavelength is measured by the rate of change of the phase with height, as seen from Fig. 4. The figure shows that the time of maximum eastward and northward winds occurred at earlier times at the higher altitudes, implying a downward phase and upward energy propagation. Long vertical wavelengths of more than 150 km are estimated during these periods. This behavior is most frequently observed during the time periods of strong enhancement of the 2-day wave activity over London (Thayaparan *et al.*, 1997).

Figure 5 shows the phase at 91 km from day number 171 to day number 220. There is a evidence of large phase shifts occurring between the bursts. These large phase shifts are generally associated with amplitude minimum between the bursts, which can be compared with amplitudes in Fig. 3. Examples can be seen near day number 195 in 1993 and day number 190 in 1994 for both the zonal and meridional components at both sites. Phase jumps of 180° are evident during these occasions, particularly near day number 190 in 1994 for the meridional component. This behavior is suggestive of beating between 2 modes, both with periods close to 2 days, although we have not pursued any attempts to isolate these components. The 180° phase jumps are also evident in filtered wind time series presented in earlier works by Craig and Elford (1981), Craig *et al.* (1983), and Poole (1990), and simultaneous observations at Sasaktoon (52°N) and Durham (43°N) given by Clark *et al.* (1994). It should be noted that although the large phase shifts are observed between the bursts, the phases generally drift slowly and steadily towards earlier times with day number during the periods of first and second enhanced wave activities (i.e., during day numbers

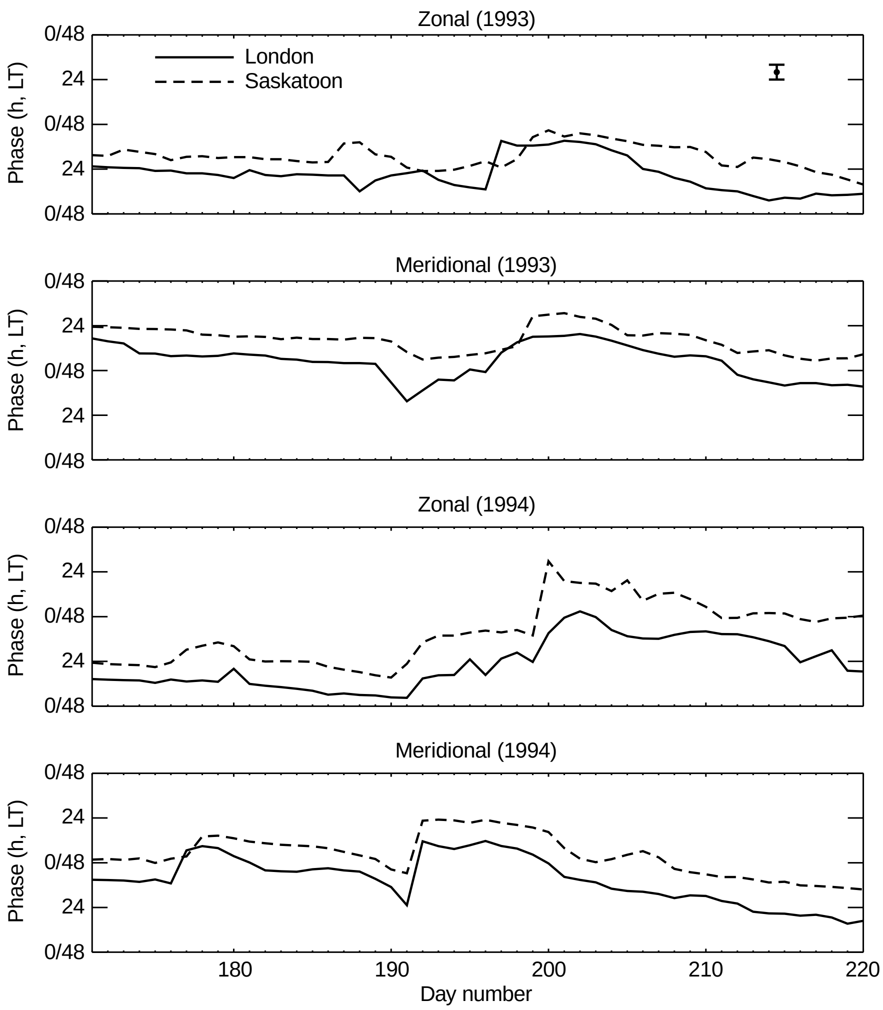

Fig. 5. Comparison of the daily phase of the 2-day wave at 91 km during day numbers 171–220 in 1993 and 1994 for the zonal and meridional components at London and Saskatoon. The phase of the 2-day wave was obtained by determining the local time of the maximum eastward and northward winds. The phase is estimated relative to 0000 LT on January 1, 1993. *Vertical bar* in the upper panel indicates the 95% confidence limits

175–185 in 1993 and 180–190 in 1994 for the first event, and during day numbers 201–210 in 1993 and 205–215 in 1994 for the second event), as are consistent with a period of less than 48 h (see later).

5 Period

In this section, although we present the period as a function of time from day number 152 to day number 270, the main focus of the wave period studies will be during the time periods of enhanced wave activity. Figure 6 shows the phase of the complex demodulated meridional component of the 2-day wave from day number 175 to 184 (first event) and from day number 201 to 210 (second event) in 1993 at both sites, using a demodulation period of 48 h. These plots are approximately linear and have positive rate of change with time. This behavior is generally observed during the time periods when the wave had a demodulated amplitude greater than 8 m/s. Since the rate of change of the demodulated phase is proportional to the difference between the demodulation frequency and the frequency of the dominant signal within the bandpass, these results clearly suggest a period less than 48 h. The fact that these phase variations are so nearly linear shows that the time interval really is dominated by the 2-day wave and that there is little interference from other components. This means we have considerable reliability in our period estimation. We now discuss the variation of the period as a function of time.

Figure 7 shows the variation of the period as a function of time in 4 day intervals, which can be compared with the amplitudes in Fig. 3. Generally the periods are between 42 h and 54 h. We draw attention to the relatively excellent agreement in period between the two sites from day number 180 to day number 220, particularly for the meridional component in both years, which seems to coincide with the enhancement or "burst" in the amplitude of the 2-day wave. The period

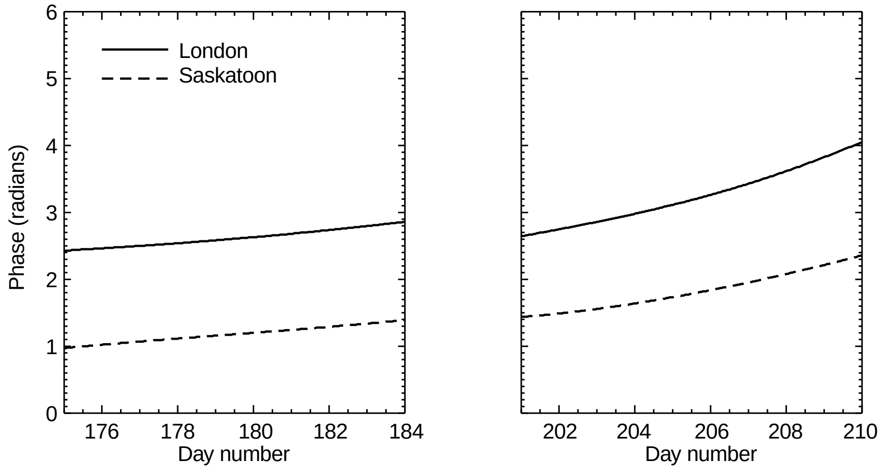

Fig. 6. The phase of the complex demodulated meridional component of the 2-day wave (*left*) from day number 175 to 184 and (*right*) from day number 201 to 210 in 1993 at both sites, using a demodulation period of 48 h

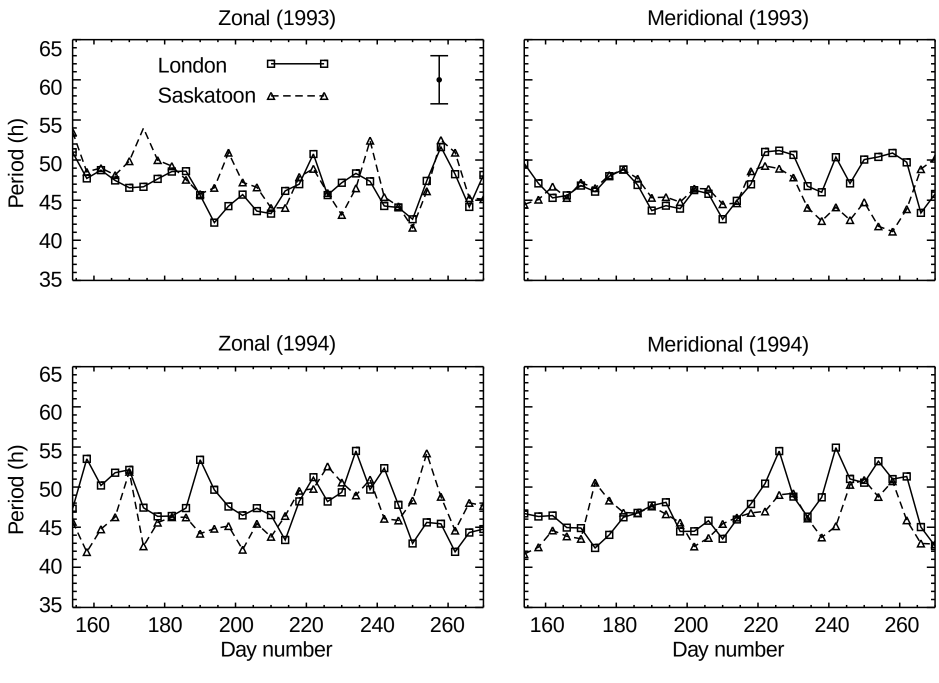

Fig. 7. The variation of the period as a function of time in 4 day intervals at 91 km for the zonal (*left*) meridional (*right*) components in London and Saskatoon from day number 152 to day number 270 for the years 1993 and 1994. *Vertical bar* in the upper panel indicates the 95% confidence limits

differs significantly between the two sites for the zonal component during this period at certain times, probably due to the small amplitudes observed over London. The mean periods during the bursts of the 2-day activity are 47.2 ± 2.8 h and 47.1 ± 2.7 h for the zonal component at the London and Saskatoon sites respectively, while the respective mean periods are 46.2 ± 2.4 h and 46.6 ± 2.5 h for the meridional component at the London and Saskatoon sites in 1993. In 1994 the mean period values are 46.4 ± 2.9 h and 47.1 ± 2.6 h for the zonal component at the London and Saskatoon sites respectively, and the respective values are 46.2 ± 2.3 h and 46.3 ± 2.5 h for the meridional component at the London and Saskatoon sites. Note that the error of the period is defined as 1.96 σ (95% confidence limits), where σ is the standard deviation for the mean (standard error). The standard deviation is estimated from the distribution of $\frac{d\Phi}{dt}$ for each wind component and site. It should be noted that the period of the 2-day wave was only taken into account when the wave had a demodulated amplitude greater than 8 m/s. After a number of tests it turns out that the results of the mean periods are even more consistent if the cutoff amplitude is increased (e.g., 15 m/s). All these results strongly suggest that the enhancement or burst of the 2-day activity occurs most frequently near a period of 46–47 h. The periods determined in the present study are therefore found to be smaller than the 51–52 h period generally suggested by the Northern Hemisphere results (e.g., Muller, 1972; Glass *et al*., 1975; Muller and Nelson, 1978; Kingsley *et al*., 1978; Stenning *et al*., 1978; Manson *et al*., 1978; Salby and Roper, 1980; Tsuda *et al*., 1988), although these other studies did not distinguish periods on the basis of wave amplitudes as we have.

To further confirm that the periods are between 46 and 47 h at both sites during the enhancement of the 2-day wave activity, we also calculated the periods using the harmonic analysis method as discussed in Sect. 2.2 and those were found consistent with the period values obtained from the complex demodulation method. A more detailed comparison between the complex demodulation and harmonic analysis methods is given by Thayaparan *et al*. (1997).

6 Amplitude spectra

Figures 1 and 3 clearly illustrate that, in each year, there are two strong bursts of the 2-day wave activity and they seem to die out abruptly after 7–10 cycles in each burst of the activity. Therefore we will concentrate on only the time periods associated with the large amplitude of the 2-day wave activity. The first event occurs simultaneously at both sites specifically from day number 175 to day number 191, and the second event occurs simultaneously from day number 201 to day number 216 in 1993. In 1994 the first event occurs simultaneously from day number 175 to day number 191 (same time period as in 1993), and the second event occurs simultaneously from day number 207 to day number 222. It should be noted that 90–95% of the total available hourly mean data were available at both sites during these period of time for the years 1993 and 1994.

Figures 8 and 9 show amplitude spectra for the two burst events discussed both for the years 1993 and 1994. Note that the ordinates of the resultant amplitude spectra have dimensions of m/s since the original amplitudes have been multiplied by a normalization constant which has dimension of Hz (e.g., Bloomfield, 1976; Bracewell, 1978). This allows one to compare qualitatively the relative amplitude variation of the 2-day (near 0.5 cycle/day) wave with the tidal components e.g., 24-h (1 cycle/day) , 12-h (2 cycles/day), and 8-h (3 cycles/day) components. The maximum amplitude values obtained from this figure are in good agreement with the values estimated by the harmonic analysis method (compare with Fig. 1). This figure shows that the amplitude of the meridional diurnal tide is significantly reduced to less than 5 m/s during the time of largest amplitude of the 2-day wave at the London site, while the amplitude values as large as 10–20 m/s are observed at the Saskatoon site in the meridional component of years 1993 and 1994. The semidiurnal tide generally attains values in excess of ~10–20 m/s during this period of time in the meridional component at both sites of years 1993 and 1994. In contrast, for the zonal component, the amplitude of the diurnal tide generally attains ~10–20 m/s at London site, and the amplitude values are significantly reduced to less than 7 m/s at the Saskatoon site in both years except from day number 175 to day number 191 in 1994. From day number 175 to day number 191 in 1994 for the zonal component the amplitude of the diurnal tide is larger (attains values as large as 20 m/s) by a factor of 2 than the 2-day wave at the London site, while at the Saskatoon site the amplitude of the 2-day wave is larger (~20 m/s) by a factor of 2 than the diurnal tide.

From Fig. 1–3 and 7–9 as well as in the results obtained for years 1993 and 1994, many similarities appear between the sets of data at the two sites. The time variation of the 2-day oscillations also suggests that the characteristic behavior is similar at both sites. Therefore we used two methods, the cross correlation and cross spectrum, between the sites to achieve quantitative results.

7 Cross-correlation

The cross-correlation method studies the variation of the cross-correlation coefficients (CCF) versus the time shift experienced by one set of data compared with the other set of data. If this coefficient varies quasi-sinusoidally versus time, the period of the curve will show the period of the dominant motion present in both records. The time shift between the origin and the time when this coefficient reaches its maximum value is equal to the phase shift of the wave between both sites.

In our analysis procedure, the original hourly mean data were subjected to a bandpass filter with cutoff period of 42 and 54 h. Thus, the tides and gravity waves are removed by this bandpass filtering. Figure 10

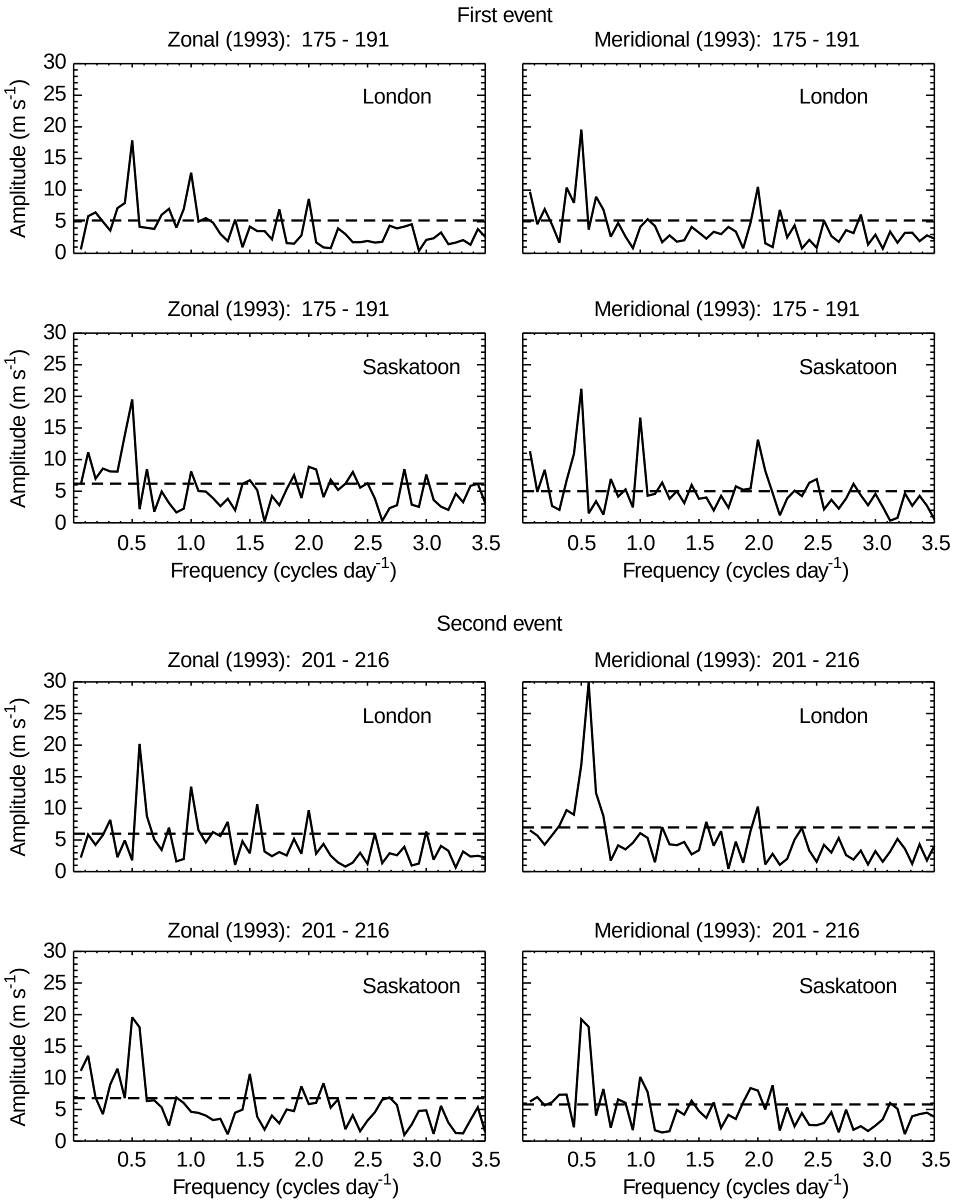

Fig. 8. Amplitude spectra for the two burst events at 91 km for the zonal (*left*) and meridional (*right*) components in London and Saskatoon in 1993. Note that the ordinates of the resultant amplitude spectra have dimensions of m/s since the original amplitudes have been multiplied by a normalization constant which has the dimension Hz (see the text for more details). *Dotted lines* indicate the 95% confidence limits

illustrates the cross-correlation between the data obtained at the London and Saskatoon sites for both the zonal and meridional components in 1993 and 1994. This figure shows quite distinctly that the same periodic motion is measured at both sites. The period of motion is the time for one complete oscillation in the CCF-time curve (Fig. 10). We can see from the figure that there are many combinations such as distance between successive amplitude maximums, distance between successive minimums, etc. to estimate the period of the dominant motion present in the data. We have used all such combinations to estimate the mean period of the 2-day wave. The associated errors are then estimated using the distribution of the periods for each component. The calculations reveal that the periods of the 2-day wave are 47.2 ± 1.8 h and 46.4 ± 1.6 h in 1993 and 47.1 ± 1.9 h and 46.2 ± 1.7 h in 1994 for the zonal and meridional components respectively. These values are consistent with the values estimated by the complex demodulation method (see Sect. 5). It is important to note that these period values were estimated when the cross-correlation values are greater than 0.4.

A significant correlation between the two sites is clearly apparent in Fig. 10 for the 2-day wave particularly in the meridional component. The peak cross-correlation values are of $\sim$0.75–0.90 in both years. These results reveal that the enhancement of the 2-day wave activity occurred with a high degree of consistency between the two sites during this period of time. On the other hand, the cross-correlation values for the zonal component are comparatively smaller, with values of $\sim$0.5 except from day number 207 to day number 222 in 1994. The plot of the correlation function from day number 207 to day number 222 in 1994 for the zonal component yield quantitative evidence that there was no correlation between the two sets of data in this time interval, showing either that there were motions with quite different periods or that there were no significant

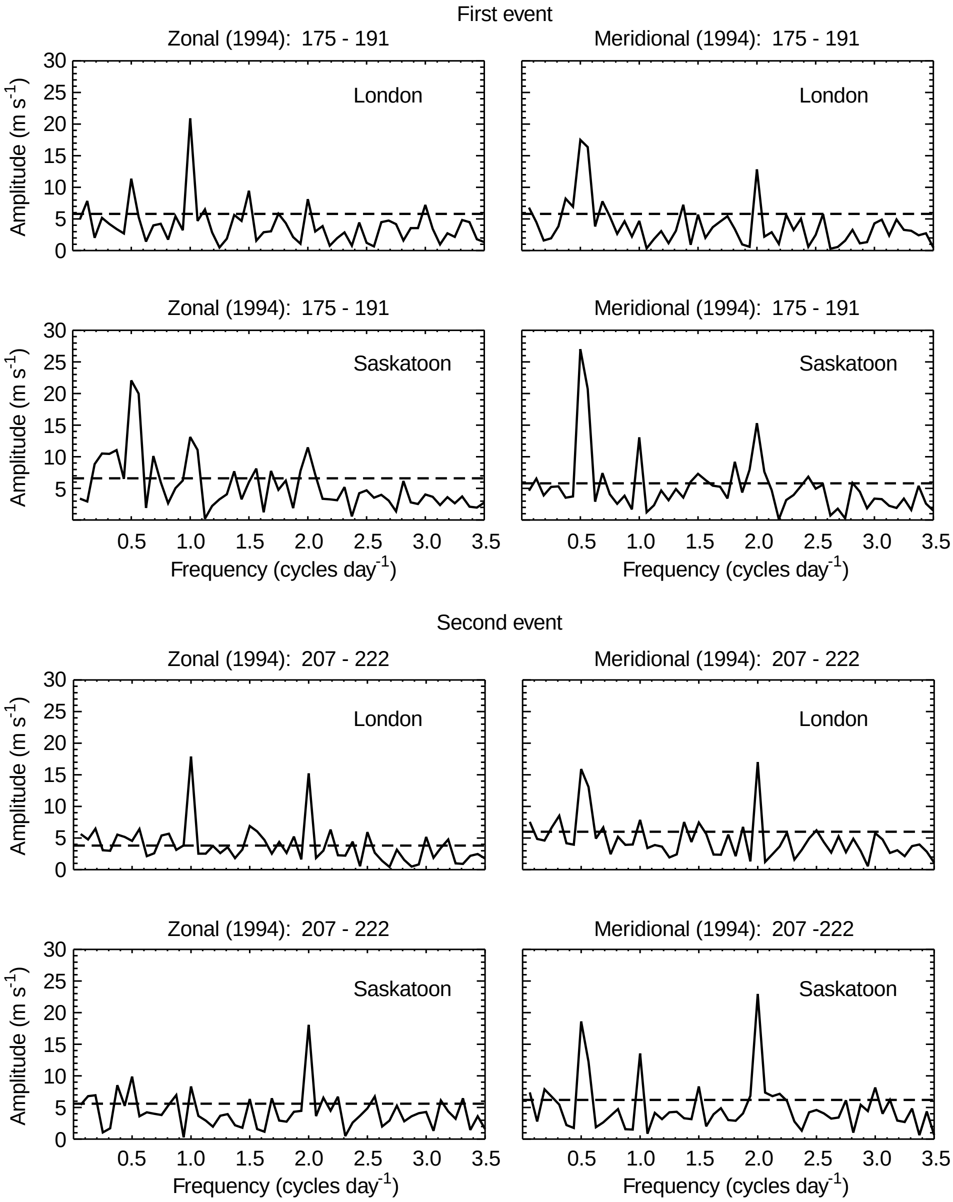

Fig. 9. Amplitude spectra for the two burst events at 91 km for the zonal (*left*) and meridional (*right*) components in London and Saskatoon in 1994. Note that the ordinates of the resultant amplitude spectra have dimensions of m/s since the original amplitudes have been multiplied by a normalization constant which has the dimension Hz (see the text for more details). *Dotted lines* indicate the 95% confidence limits

periodic motions at both sites. The latter possibility agrees with Fig. 3.

The time lags for maximum correlation are found to occur between 10 and 11 h for the meridional component in 1993. The respective value is 12–16 h for the meridional component in 1994. For the zonal component the time lags for maximum correlation occur between 9 and 10 h in 1993, and occur near 16 h in 1994. The physical significance of these results will be discussed in the following section.

8 Cross-spectrum

The cross-spectrum method gives not only information about the dominant periodicity simultaneously observed at two sites, but also sets out quantitatively the values of amplitude, period, and phase difference of every motion present. The main purpose of this analysis in this present study is to estimate the precise phase differences between the two sites in order to estimate the zonal wave number of the travelling westward wave.

The zonal wave number of the 2-day wave can be estimated by simultaneous comparisons of its phase at two sites situated at similar latitudes but separated in longitude. If we interpret the phase differences at the two sites as the effect of a westward propagating wave then we can calculate its zonal wave number from the apparent phase speed by using the relationship, $k = \frac{360}{T}\frac{\Delta T}{\Delta d}$ (e.g., Muller and Nelson, 1978), where k is the zonal wave number, T is the wave period, ΔT is the time difference between the two sites, and Δd is the longitudinal difference between the observational sites in degrees. It has already been shown, in the previous sections, that a 2-day wave period of $\sim$46.5 h is typical at both sites during the time period of strong 2-day wave activity. It is desirable for the two sites to simultaneously sample the same cycle, i.e., to be within 120° of

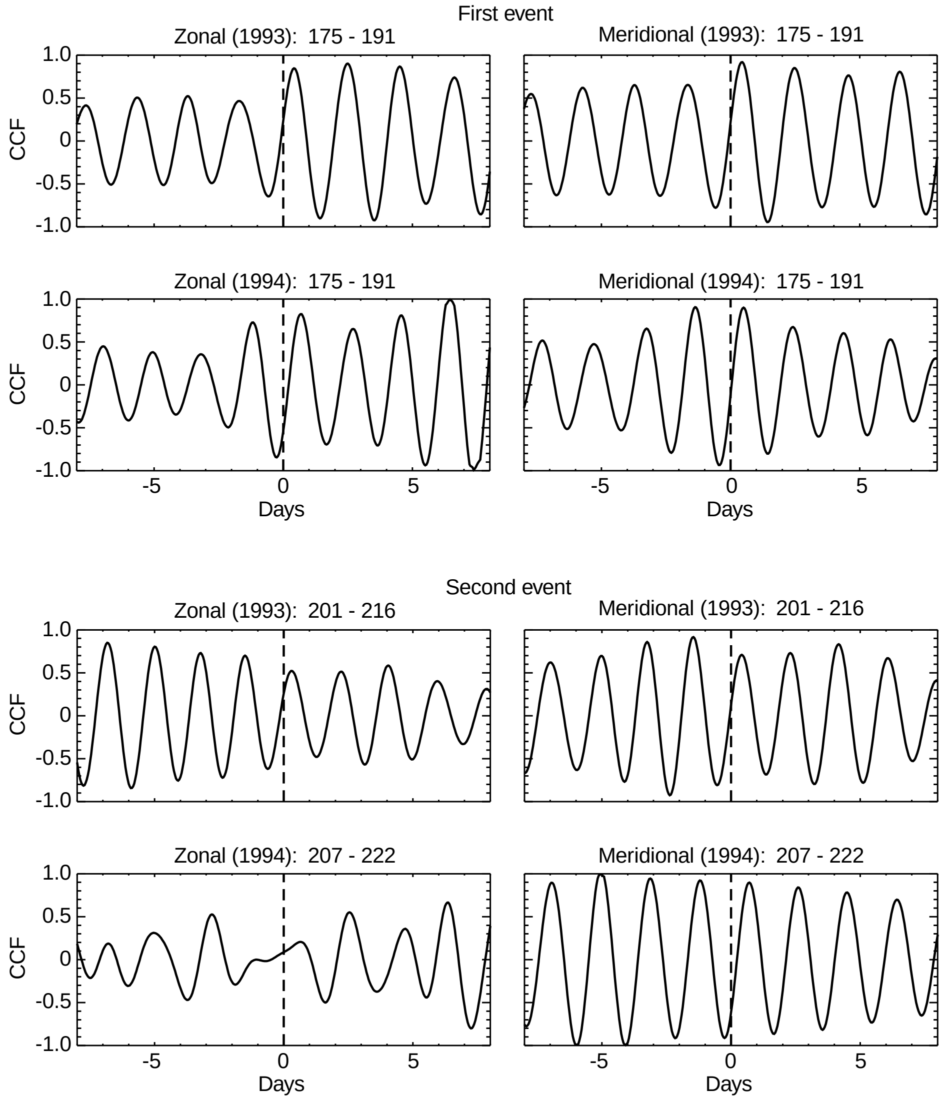

Fig. 10. Cross-correlation between the data obtained at London and Saskatoon for the zonal (*left*) and meridional (*right*) components in 1993 and 1994 for the two burst events (see the text for more details)

longitude (which assumes the zonal wave number 3 pattern) of each other, because the wave structure may be different for each cycle as they circle the globe. The satellite temperature observations clearly show that each of the three cycles of the zonal wave number 3 pattern differ (Rodgers and Prata, 1981). A zonal wave number of 3 means that a wave will have 3 cycles circling the globe. The geographical separation of London and Saskatoon is 9° in latitude and 26° in longitude. On the other hand, the closer the sites the smaller the phase difference and hence the larger the relative error in its estimate. As an example, for an error of 1 h in each phase estimate, the difference will produce an error of $\sim$0.3 in the zonal wave number. If the 2-day wave is assumed to be due to a westward propagating wave with a zonal wave number 3, and also assuming there is no phase change with latitude, then the 2-day wave at London should lead that at Saskatoon by $\sim$10 h, i.e., the crest of the wave moves from east to west.

Another approach is to use the phase of the cross-spectrum of the two wind time series. This method yields a measure of the average phase difference of the time series. Let us check whether such a motion could account for the experimental zonal wave number 3. We have examined 6 intervals of 8-day data sets from day number 175 to day number 222. One example of the normalized cross-spectrum between the two sites using data from day number 183 to day number 190 for the meridional component in 1994 is shown in Fig. 11. We have adopted a 8-day data set because Fig. 3 suggests that this is long enough to give reasonable significance to our results, and will also allow us to create a reliable error estimate for the cross-spectral phase. Figure 11 shows distinctly that the 2-day oscillation is the dominant feature of the cross-spectrum during this period of time. This means that, whenever a distinct peak in the spectrum appears in the London data, it exists at Saskatoon too. Similar behavior is frequently observed during other periods of time. These results further confirm that from day number 175 to day number 222, the same periodic motions are simultaneously detected over London and Saskatoon. Tables 1 and 2 give the apparent phase lag between the two sites for 6 independent periods in 1993 and 1994 respectively. The results

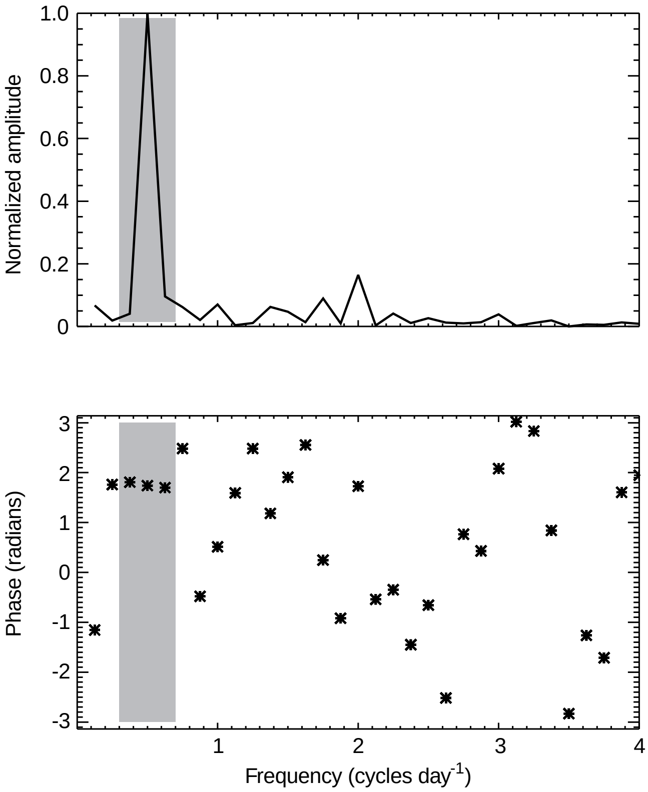

Fig. 11. Normalized cross-spectrum of the meridional wind component between London and Saskatoon from day number 183 to day number 190 in 1994. The phase is the number of radians by which London leads Saskatoon

show that the London site leads the Saskatoon site by $\sim 9.7 \pm 1.4$ h and $\sim 10.8 \pm 0.6$ h for the zonal and meridional components respectively in 1993. The corresponding zonal wave numbers are 2.9 ± 0.4 and 3.2 ± 0.2 for the zonal and meridional components. For the year 1994 we divided the data into 2 sets of data, i.e. from day number 175 to day number 198 and from day number 199 to day number 222, because of a significant increase in the estimated of the time lag (see also Table 2). It turns out that the London site leads the Saskatoon site by $\sim 10.0 \pm 2.7$ h during the first half of the time period (175–198), and by $\sim 16.8 \pm 0.8$ h during the second half of the time period (199–222) for the meridional component. The corresponding zonal wave numbers are 3.0 ± 0.8 and 5.0 ± 0.2. For the zonal component the London site leads Saskatoon by $\sim 16.4 \pm 0.2$ h during the first half of the time period (175–198), and the values are not shown during the second half of the time period in Table 2 because the amplitudes of the cross-spectra are very small, so that the phase determinations are of dubious quality. It should be emphasized that the values for the zonal component during the first half of the time period in 1994 should also be treated with caution, since relatively small amplitudes are associated with the cross-spectrum. It must be also emphasized here that the phase profiles of the 2-day wave are almost constant with height suggesting the presence of evanescent or long vertical wavelength (>150 km) behavior during the time periods of strong enhancement of the 2-day wave activity Thayaparan *et al.*, 1997).

The zonal wave number was also calculated from a smoothed cross-spectrum as a cross-check. This was achieved by applying a 3 point running mean to the separate complex amplitude spectra prior to computing the cross-spectrum. However, there is little difference between the results from the raw and the smoothed cross-spectra. We wish to note that the estimated phase lags are consistent with the values obtained from the cross-correlation method in the previous section (see Fig. 10 and the respective text in Sect. 7). Overall, our results suggest that the 2-day wave is a westward propagating Rossby-gravity wave of zonal wave number 3 specially at large amplitudes. As such, our results appear consistent with the studies by Salby (1981) and Hagan *et al.* (1993) supporting a normal mode interpretation of the wave motion following excitation. Other previous Northern Hemisphere observations by ground-based and satellite instruments also support our estimation of a zonal wave number 3 (e.g., Muller and Nelson, 1978; Craig *et al.*, 1983; Phillips, 1989; Poole, 1990; Clark *et al.*, 1993; Rodgers and Prata, 1981; Wu *et al.*, 1993). A zonal wave number 5 was also reported by Kalchenko (1987).

This estimation of the zonal wave number of the 2-day wave hinges on the premise that the phase of the 2-day wave is invariant with latitude since we assume in our analysis that the latitudinal spacing between the two sites can be neglected. However, both numerical simulations (e.g., Salby, 1981) and High Resolution Doppler

Table 1. The phase relationship of the 2-day wave components between London and Saskatoon in 1993. The table shows the number of hours by which London leads Saskatoon

Interval (day numbers)	Zonal (hours)	Meridional (hours)
175–182	8.8	10.4
183–190	10.9	9.3
191–198	–	9.7
199–206	6.4	10.1
207–214	12.7	13.5
215–222	–	11.5
Average	9.7 ± 1.4	10.8 ± 0.6

Table 2. The phase relationship of the 2-day wave components between London and Saskatoon in 1994. The table shows the number of hours by which London leads Saskatoon

Interval (day numbers)	Zonal (hours)	Meridional (hours)
175–182	16.2	7.3
183–190	16.5	12.7
191–198	–	–
Average	16.4 ± 0.2	10.0 ± 2.7
199–206	–	17.4
207–214	–	15.2
215–222	–	17.8
Average	–	16.8 ± 0.8

Imager (HRDI) observations on the Upper Atmosphere Research Satellite (UARS) (Wu *et al.*, 1993) indicate that the 2-day wave can undergo a latitudinal phase shift near 91 km. It is important to point out here that HRDI results are limited to a single month (January) over a limited period (8 days) of observations and results are only available from 60°S to 20°N latitude. Recently, Meek *et al.* (1996), by combining data from nine meteor and MF radars around the globe, claimed that they do not observe any significant latitudinal variation of the phase.

However, in order to obtain some error estimates, we will consider the effects of a latitudinal variation of phase. If we use same model calculation of Meek *et al.* (1996), i.e., a shift of 0.8° longitude per 1° of latitude, the estimation shows that the zonal wave number 3 might appear as either a zonal wave number 2 or 4 and the zonal wave number 5 might appear as either a zonal wave number 4 or 6, within the error bars of the data. Therefore, we emphasize that priority should be given to the consideration of systematic errors of this kind when estimating the zonal wave number, and one must be careful in the interpretation of the results. Further global observations are required in order to resolve questions about the importance of the latitudinal phase shift in the estimation of the zonal wave number.

The phase relationship between the wind components, i.e., the zonal and meridional components, is estimated by using the cross-spectrum method, in a similar fashion to the phase relationship obtained between the sites. An example of the cross spectrum of the winds at London is illustrated in Fig. 12. Tables 3 and 4 give the phase relationship between the zonal and meridional components at each sites in 1993 and 1994 respectively. The results show that the meridional component leads the zonal component by $\sim 12.6 \pm 1.7$ h and $\sim 13.1 \pm 1.1$ h at the London and Saskatoon sites respectively in 1993. These values are $\sim 10.2 \pm 1.9$ h and $\sim 13.6 \pm 0.7$ h at the London and Saskatoon sites respectively in 1994. These results strongly suggest that the components of the 2-day wave are nearly in-quadrature during the time intervals of strongest 2-day wave activity (i.e., for amplitudes greater than 8 m/s), indicating clockwise rotation of the wind vector (looking from above).

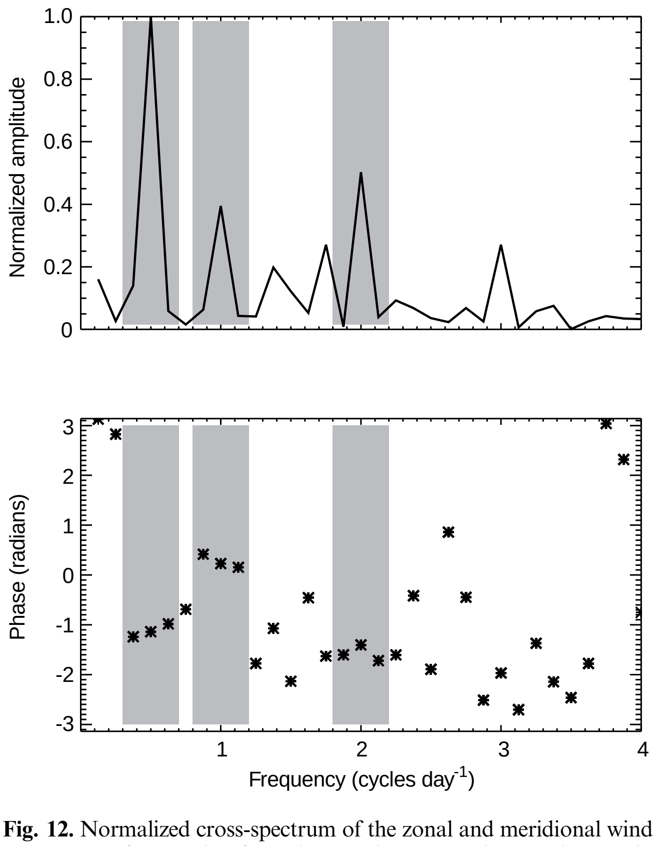

Fig. 12. Normalized cross-spectrum of the zonal and meridional wind components for London from day number 183 to day number 190 in 1994. The phase is the number of radians by which the meridional leads the zonal component

9 Summary and conclusion

Simultaneous observations between the London and Saskatoon sites have shown the existence of the 2-day wave during the late June-early August months, although these observations indicate the presence of the 2-day wave at other times of the year in 1993 and 1994. A subsidiary maximum of about 70% of the summer peak, appears during the late April–May months. The amplitudes of the meridional components (20–30 m/s) are generally larger than the zonal component (15–20 m/s) at the London site in both years. In contrast, at the Saskatoon site the amplitudes of the zonal components ($\sim$30 m/s) are larger than the meridional component

Table 3. The phase relationship of the 2-day wave wind components at each site in 1993. The table shows the number of hours by which the meridional leads the zonal component

Interval (day numbers)	London (hours)	Saskatoon (hours)
175–182	11.7	10.0
183–190	11.9	13.8
191–198	–	15.7
199–206	17.4	14.2
207–214	9.5	15.5
215–222	–	9.2
Average	12.6 ± 1.7	13.1 ± 1.1

Table 4. The phase relationship of the 2-day wave wind components at each site in 1994. The table shows the number of hours by which the meridional leads the zonal component

Interval (day numbers)	London (hours)	Saskatoon (hours)
175–182	–	14.4
183–190	8.3	12.8
191–198	–	15.3
199–206	12.0	11.5
207–214	–	–
215–222	–	13.9
Average	10.2 ± 1.9	13.6 ± 0.7

($\sim$25 m/s) in 1993, but in 1994 both the zonal and meridional components have somewhat comparable amplitudes (25–30 m/s). The amplitude variations with latitude suggest that the amplitude maximizes at low latitudes. The meridional amplitudes are comparable at London than at Saskatoon, and the zonal amplitudes at Saskatoon is larger by a factor of 2–3 than at London. Amplitudes vary from year to year but it is clear that the summer amplitude maximum is generally confined to a duration of about 50 days.

The period of the 2-day wave was determined by the complex demodulation method, and is found to change with time. During the bursts of the 2-day activity (i.e., specially at large amplitudes) the mean periods are in the 46–47 h range at both London and Saskatoon sites for the zonal and meridional components in 1993 and 1994. It should be noted that these values for the periods are estimated when the amplitudes are greater than 8 m/s. These values are shown to be consistent with the values obtained from the cross-correlation analysis method. The periods determined from the present study are found to be smaller than the 51–52 hours period often suggested by other Northern Hemisphere results, although the periods of the wave are found to vary in the 42–54 h range when amplitudes are smaller. Note that Meek *et al.* (1996) reported that periods of the wave at Saskatoon during 1991/1992 ranged from 43 to 52 h during the summer.

A striking similarity appears between the 2-day waves at London and Saskatoon. Our observations show significant correlation between the two sites of the 2-day wave during time periods of strong 2-day activity. The peak cross-correlation coefficient values are found to be between 0.75 and 0.90, particularly in the meridional component in 1993 and 1994.

Our results strongly suggest that the 2-day wave is a westward propagating Rossby-gravity wave of zonal wave number 3 (specially at large amplitudes), assuming the phase difference to be due solely to the difference in longitude. A possible connection with the zonal wave number 5 is suggested at one time (early August) in 1994. These results are independently determined by the cross-spectrum and cross-correlation methods. Note that Meek *et al.* (1996) reported a zonal wave number 4 between Saskatoon and other mid-latitude radar observations in 1992, however, the choice between zonal wave numbers 4 and 3 was not clear in 1991.

The phase relationship between the zonal and meridional components was studied at the London and Saskatoon sites using the cross-spectrum method. It was found that the meridional component leads the zonal component by $\sim$10–13 hours specially at large amplitudes, suggesting the wave components are nearly in quadrature and indicating clockwise rotation of the wind vector (looking from above). Our observations showed that there is evidence of large phase shifts occurring between the bursts, and these large shifts are generally associated with amplitude minimum between the bursts. Phase jumps up to 180° are observed during these occasions. However, the phases show little variation with time when the amplitude is large.

Finally, in order to study the complete nature of the 2-day wave at mid-latitudes, it is imperative to continue these investigations. Coordination and intercomparisons are required in order to resolve questions about the importance of the latitudinal phase shift in the estimation of the zonal wave number, the generating mechanism as well as to understand better the role of the 2-day wave in the middle atmosphere.

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References

Ball, S. M., Upper atmosphere tides and gravity waves at mid- and low-latitudes, PhD Thesis, Department of Physics, University of Adelaide, Adelaide, Australia, 1981.

Bloomfield, P., *Fourier analysis of time series: an introduction*, Wiley and Sons, New York, USA, 1976.

Bracewell, R. N., *The Fourier transform and its applications*, McGraw-Hill, New York, USA, 1978.

Brillinger, D. R., and P. R., Krishnaiah, *Time series in the Frequency domain*, Elsevier Science New York, USA, 1983.

Burks, D., and C. Leovy, Planetary waves near the mesospheric easterly jet, *Geophys. Res. Lett.*, **13,** 193–196, 1986.

Cevolani, G., S. P. Kingsley, and G. Muller, Three-station meteor wind observations in northern Europe during summer 1980, *J. Atmos. Terr. Phys.*, **45,** 275–280, 1983.

Clark, R. R., Upper atmosphere wind observations of waves and tides with the UNH meteor radar system at Durham 43°N (1977, 1978 and 1979), *J. Atmos. Terr. Phys.*, **45,** 621–627, 1983.

Clark, R. R., The quasi 2-day wave at Durham (43°N); solar and magnetic effects, *J. Atmos. Terr. Phys.*, **51,** 617–622, 1989.

Clark, R. R., A. C. Current, A. H. Manson, C. E. Meek, S. K. Avery, S. E. Palo, and T. Aso, Global properties of the 2-day wave from mesosphere-lower thermosphere radar observations, *J. Atmos. Terr. Phys.*, **43,** 1279–1288, 1994.

Coy, L., A possible 2-day oscillation near the tropical stratopause, *J. Atmos. Sci.*, **36,** 1615–1618, 1979.

Craig, R. L., R. A. Vincent, G. J. Fraser, and M. J. Smith, The quasi 2-day wave near 90 km altitude at Adelaide (35°S), *Nature*, **287,** 319–302, 1980.

Craig, R. L., and W. G. Elford, Observations of the quasi 2-day wave in the Southern Hemisphere mesosphere, *J. Atmos. Terr. Phys.*, **43,** 1051–1056, 1981.

Craig, R. L., R. A. Vincent, S. P. Kingley, and H. G. Muller, Simultaneous observations of the quasi 2-day wave in the Northern and Southern Hemispheres, *J. Atmos. Terr. Phys.*, **45,** 539–541, 1983.

Forbes, A. M. G., Fourier transform filtering, *J. Geophys. Res.*, **93,** 6958–6962, 1988.

Fritts, D. C., and J. R. Isler, Mean motions and tidal and two-day structure and variability in the mesosphere and lower thermosphere over Hawaii, *J. Atmos. Sci.*, **51,** 2145–2164, 1994.

Glass, M., J. L. Fellous, M. Massebeuf, A. Spizzichino, I. A. Lysenko, and Y. I. Portniagin, Comparison and interpretation of the results of simultaneous wind measurements in the lower thermosphere at Garchy (France 3°E) and Obninsk (USSR 36°E) by meteor technique, J. *Atmos. Terr. Phys.*, **37,** 1077–1087, 1975.

Gregory, J. B., C. E. Meek, A. H. Manson, and D. G. Stephenson, Development in the radiowave drifts technique for measurement of high altitude winds, *J. Appl. Meteorol.*, **18,** 682, 1979.

Hagan, M. E., J. M. Forbes, and F. Vial, Numerical investigation of the propagation of the quasi 2-day wave into the lower thermosphere, *J. Geophys. Res.*, **98,** 23,193–23,205, 1993.

Harris, F. J., On the use of windows for harmonic analysis with the discrete Fourier transform, *Proceedings of the IEEE*, **66,** January, 1978.

Harris, T. J., Large-scale dynamics of the upper mesosphere and lower thermosphere, PhD Thesis, Department of Physics, University of Adelaide, Adelaide, Australia, 1993a.

Harris, T. J., A long-term study of the quasi 2-day wave in the middle atmosphere, *J. Atmos. Terr. Phys.*, **55,** 1993b.

Harris, T. J., and R. A. Vincent, The quasi 2-day wave observed in the equatorial middle atmosphere, *J. Geophys. Res.*, **98,** 10,481–10,490, 1993.

Hocking, W. K., and T. Thayaparan, Simultaneous and co-located observations of winds and tides by MF and meteor radars over London, Canada (43°N, 81°W) during 1994–1996, *Radio Sci.*, in press, 1997.

Hunt, B. G., The 2-day wave in the middle atmosphere as simulated in a general circulation model extending from the surface to 100 km, *J. Atmos. Terr. Phys.*, **43,** 1143–1154, 1981.

Ito, R., T. Tsuda, T. Aso, and S. Kato, Long period oscillations in the meteor winds observed over Kyoto during 1978–1983, *J. Geomagn. Geoelectr.*, **36,** 173–188, 1984.

Kalchenko, B., Characteristics of atmospheric disturbances with a quasi 2-day period, in *Handbook for MAP*, 25, SCOSTEP Secretariat, University of Illinois, Urbana, USA, 112–118, 1987.

Kingsley, S., H. Muller, L. Nelson, and A. Scholefield, Meteor winds over Sheffield, *J. Atmos. Terr. Phys.,* **40,** 917–922, 1978.

Longuet-Higgins, M. S., The eigenfunctions of Laplace's tidal equation over a sphere, *Philos. Trans. Roy. Soc. London*, **A262,** 511–607, 1968.

Manson, A. H., and C. E. Meek, Dynamics of the middle atmosphere at Saskatoon (52°N, 107°W): a spectral study during 1981, 1982, *J. Atmos. Terr. Phys.*, **48,** 1039–1055, 1986.

Manson, A. H., J. B. Gregory, C. E. Meek, and D. G. Stephenson, Winds and wave motions to 110 km at mid-latitudes, *J. Atmos. Sci.*, **35,** 592–599, 1978.

Manson, A. H., C. E. Meek, J. B. Gregory, and D. K. Chakrabarty, Fluctuations in tidal (24-, 12-h) characteristics and oscillations (8-h-5-d) in the mesosphere and lower thermosphere (70–110 km): Saskatoon (52°N, 107°W), 1979–1981, *Planet Space Sci.*, **30,** 1283–1294, 1982.

Massebeuf, M., R. Bernard, J. L. Fellous, and M. Glass, Simultaneous meteor radar observations at Monpazier (France, 44°N) and Punta Borinquen (Puerto Rico, 18°N) – mean zonal wind and long period waves, *J. Atmos. Terr. Phys.*, **43,** 535–542, 1981.

Meek, C. E., An efficient method for analysing ionospheric drifts data, *J. Atmos. Terr. Phys.*, **41,** 251–258, 1980.

Meek, C. E., A. H. Manson, S. J. Franke, W. Singer, P. Hoffmann, R. R. Clark, T. Tsuda, T. Nakamura, M. Tsutsumi, M. Hagan, D. C. Fritts, J. Isler, and Y. I. Portnyajin, Global study of Northern Hemisphere quasi 2-day wave events in recent summers near 90 km altitude, *J. Atmos. Terr. Phys.*, **58,** 1401–1411, 1996.

Muller, H. G., Long-period meteor wind oscillations, *Philos. Trans. R. Soc. London*, **Ser. A, 271,** 585–598, 1972.

Muller, H. G., and L. Nelson, A travelling quasi-2-day in the meteor region, *J. Terr. Atmos. Phys.*, **40,** 761–766, 1978.

Palo, S. E., and S. K. Avery, Observations of the meridional quasi 2-day wave in the mesosphere and lower thermosphere at Christmas Island, in *The upper mesosphere and lower thermosphere: a review of experiment and theory*, Geophysics Monograph Series, **87,** pp. 101–110, 1995.

Park, B., and M. Muller, Random number generators: good ones are hard to find, *Communication of the ACM*, October 1988, 31, (10) 1192, 1988.

Phillips, A., Simultaneous observations of the quasi 2-day wave at Mawson, Antarctica, and Adelaide, South Australia, *J. Atmos. Terr. Phys.*, **51,** 119–124, 1989.

Pfister, L., Baroclinic instability of easterly jets with application to the summer mesosphere, *J. Atmos. Sci.*, **42,** 313–330, 1985.

Plumb, R. A., Baroclinic instability of the summer mesosphere: a mechanism for the quasi 2-day wave?, *J. Atmos. Sci.*, **40,** 262–270, 1983.

Plumb, R. A., R. A. Vincent, and R. L. Craig, The quasi 2-day wave event of January 1984 and its impact on the mean mesospheric circulation, *J. Atmos. Sci.*, **44,** 3030–3036, 1987.

Poole, L. M. G., Characteristics of the mesospheric two day wave as observed at Grahamstown (33.3°S, 26.5°E), *J. Atmos. Terr. Phys.*, **52,** 259–268, 1990.

Randel, W. J., Observations of the 2-day wave in NMC stratospheric analyses, *J. Atmos. Sci.*, **51,** 306–313, 1993.

Reddi, C. R., A. Geetha, and K. R. Lekshmi, Quasi 2-day wave in the middle atmosphere over Trivandrum, *Ann. Geophysicae*, **6,** 231–238, 1988.

Rodgers, C. D., and A. Prata, Evidence for a travelling 2-day wave in the middle atmosphere, *J. Geophys. Res.*, **86,** 9661–9664, 1981.

Salby, M. L., The 2-day wave in the middle atmosphere: observations and theory, *J. Geophys. Res.*, **86,** 9654–9660, 1981.

Salby, M. L., and Roper, R. G., Long-period oscillation in the meteor region, *J. Atmos. Sci.*, **37,** 237–244, 1980.

Stenning, R., C. E. Meek, A. H. Manson, and D. Stephensen, Winds and wave motions to 110 km at mid-latitudes, *J. Atmos. Sci.*, **35,** 2194–2204, 1978.

Thayaparan, T., Large- and medium-scale dynamics in the mesosphere and lower thermosphere measured by MF and meteor VHF radars, PhD Thesis, Department of Physics, University of Western Ontario, Ontario, Canada, 1995.

Thayaparan, T., W. K. Hocking, and J. MacDougall, Middle atmospheric winds and tides over London, Canada (43°N, 81°W) during 1992–1993, *Radio Sci.*, **30,** 1293–1309, 1995a.

Thayaparan, T., W. K. Hocking, and J. MacDougall, Observational evidence of tidal/gravity wave interactions using the UWO 2 MHz radar, *Geophys. Res. Lett.*, **22,** 373–376, 1995b.

Thayaparan, T., W. K. Hocking, and J. MacDougall, Amplitude, phase, and period variations of the quasi 2-day wave in the mesosphere and lower thermosphere over London, Canada (43°N, 81°W), during 1993 and 1994, *J. Geophys. Res.*, in press, 1997.

Tsuda, T., S. Kato, and R. A. Vincent, Long period oscillations observed by the Kyoto meteor radar and comparison of the quasi-2-day wave with Adelaide HF radar observations, *J. Atmos. Terr. Phys.*, **50,** 225–230, 1988.

Wu, D. L., P. B. Hays, W. R. Skinner, A. R. Marshall, M. D. Burrage, R. S. Lieberman, and D. A. Ortland, Observations of the quasi 2-day wave from the high resolution Doppler imager on UARS, *Geophys. Res. Lett.*, **20,** 2853–2856, 1993.